

Optically observable zero-age main-sequence O stars

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A list of 50 optically observable O stars that are likely on or very near the ZAMS is presented. They have been selected on the basis of five distinct criteria, although some of them exhibit more than one. Three of the criteria are spectroscopic (He II $\lambda 4686$ absorption stronger than in normal luminosity class V spectra, abnormally broad or strong Balmer lines, weak UV wind profiles for their spectral types), one is environmental (association with dense, dusty nebular knots), and one is photometric (derived absolute magnitudes fainter than class V). Very few of these stars have been physically analyzed, and they have not been considered in the current framework of early massive stellar evolution. In particular, they may indicate that the earliest, embedded phases are not as large a fraction of the main-sequence lifetimes as is currently believed. Detailed analyses of these objects will likely prove essential to a complete understanding of the early evolution of massive stars.

1. Introduction

It is often stated that zero-age main-sequence (ZAMS) O stars should not be and are not observed. This view arises from at least three sources: star-formation theory, which suggests that the embedded accretion (merger?) phases constitute a significant fraction of the main-sequence lifetimes of massive stars (2.5 Myr for the most massive); statistical studies of UCHII and IR objects relative to optically observed ones; and detailed physical analyses of optical O-star samples that find very few on the ZAMS. For instance, Repolust, Puls, & Herrero (2004) analyzed 24 relatively bright O stars and found only one, HD 93128 in the Carina Nebula compact cluster Trumpler 14, on the ZAMS. However, selection effects may be contributing to this view. If the optically observable near-ZAMS phase of massive stars is relatively brief, it must be sought in very young regions, which may be distant and/or extincted. Also, it is possible that some IR objects are no longer embedded, but rather viewed along unfavorable sightlines in galactic disks or through local, peripheral remanent dust clouds. For example, if we did not have such fortunate lines of sight toward NGC 3603 and 30 Doradus, we might be quite confused about their evolutionary status (Walborn 2002). Such must be the case for at least some objects.

Over the past 35 years, this author and others have encountered numerous optical O stars that appear to be very young for various morphological reasons. These results are scattered throughout the literature and have not been generally recognized by star-formation and evolutionary specialists, or even by quantitative spectroscopists, whose analyses are essential for the former. It is hoped that this summary presentation will provide a useful stimulus toward rectifying the omission. It will be seen that many of the objects in question are in the Magellanic Clouds. But also, HD 93128 will reappear in the plot.

2. Categories of candidate ZAMS O stars

The current sample of 50 optically observable, likely ZAMS O stars is listed in Table 1, along with some normal standard stars for comparison. The ZAMS candidate list was

ID	Sp Type	V	$B - V$	$E(B - V)$	$V_0 - M_V$	M_V	Comment	Reference
V_z								
HD 64315	O6 Vnz	9.24	0.25	0.57	13.2	-5.7		V. Niemela priv. com (Fig. 3)
HD 64568	O3 V((f*))	9.39	0.11	0.43	13.2	-5.1	also sublum	" (Fig. 3)
HD 92206B	O6 V((f))	9.16	0.17	0.49	12.2	...		N. Morrell priv. com
HD 93128	O3.5 V((f+))	8.77	0.24	0.56	12.2	-5.1	also sublum	Walborn 1973b, 1982, 1995
HD 93129B	O3.5 V((f+))	8.9	0.22	0.54	12.2	-4.9	also sublum	"
CPD-58°2611	O6 V((f))	9.63	0.28	0.60	12.2	-4.4	also sublum	"
CPD-58°2620	O6.5 V((f))	9.27	0.18	0.50	12.2	-4.4	also sublum	"
HDE 303311	O5 Vz	9.05	0.13	0.45	12.2	-4.5	also sublum	V. Niemela priv. com (Fig. 3)
FO 15	O5.5 Vz	12.05	...	1.21	12.2	-4.2	also sublum, $R = 4.15$	Niemela et al. 2006 (Fig. 3)
HD 150135	O6.5 Vz((f))	6.89	0.17	0.49	...	...		Niemela & Gamen 2005 (Fig. 3)
HD 152590	O7.5 V	8.42	0.14	0.46	11.5	-4.5	also sublum	Martins et al. 2005
LH2-96	O7.5 Vz	14.95	-0.17	0.15	18.6	-4.1	also sublum	Parker et al. 2001
LH9-1486	O6.5 Vz	14.20	-0.21	0.11	18.6	-4.7	also sublum	Parker et al. 1992
LH10-3073	O6.5 Vz	14.71	-0.10	0.22	18.6	-4.6	also sublum	" (Fig. 2)
LH10-3102	O7 Vz	13.55	-0.10	0.22	18.6	-5.7		" (Fig. 2)
LH10-3126	O6.5 Vz	14.32	0.00	0.32	18.6	-5.2	also Vb	" (Fig. 2)
LH10-3204	O6-7 Vz	14.02	-0.17	0.15	18.6	-5.0	also sublum	"
30 Dor-171	O6-8 Vz	15.67	0.26	0.58	18.6	-4.7		Walborn & Blades 1997
30 Dor-341	O8-9 Vz	14.40	-0.03	0.28	18.6	-5.0		"
30 Dor-803	O3-5 Vz	15.61	0.33	0.65	18.6	-4.9	also sublum	"
30 Dor-1340	O7 Vz	14.94	0.01	0.33	18.6	-4.6		"
30 Dor-1643	O3-5 Vz	15.51	0.15	0.47	18.6	-4.5	also sublum	"
30 Dor-1892	O8.5 Vz	15.63	0.23	0.54	18.6	-4.6		"
30 Dor-2270	O7 Vz	15.31	0.09	0.41	18.6	-4.5	also sublum	Parker 1993
NGC 346-113	OC6 Vz	14.93	-0.22	0.10	19.1	-4.5	also sublum	Walborn et al. 2000
V_b								
θ^1 Ori C	O6 Vp var	5.13	0.00	0.32	8.3	-4.5	also wk wind, sublum, $R = 5.5?$	Morgan & Keenan 1973
θ^2 Ori A	O9.5 Vp	5.08	-0.11	0.19	8.3	-4.0	$R = 5.5?$	
HD 92206C	O8.5 Vp	9.05	0.15	0.46	12.2	-4.5		Walborn 1982
Herschel 36	O7.5 V(n)	10.30	...	0.85	10.9	-5.2	also knot, $R = 5.39$	Arias et al. 2006
<i>Weak Winds</i>								
HD 5005A	O6.5 V((f))	7.76	...	0.42	...	...	from $b - y$	Walborn et al. 1985
HD 42088	O6.5 V	7.55	0.06	0.38	...	...	also Vz, "knot"	Martins et al. 2005
HD 54662	O6.5 V	6.21	0.03	0.35	...	...		Walborn et al. 1985

TABLE 1. O-Type ZAMS Candidates

ID	Sp Type	V	$B - V$	$E(B - V)$	$V_0 - M_V$	M_V	Comment	Reference
<i>Knots</i>								
N11A-7	O3-6 V	14.69	...	0.19	18.6	-4.5	y , also Vz, sublum	Heydari-Malayeri et al. 2001 (Fig. 2)
30 Dor-409A	O8.5 V	17.05	...	0.56	18.6	-3.3	WFPC2, also sublum	Walborn et al. 2002a, CHORIZOS
30 Dor-409B	O9 V	17.08	...	0.49	18.6	-3.0	WFPC2, also sublum	"
30 Dor-1201	O9.5 V	15.83	...	0.37	18.6	-3.9	WFPC2	"
30 Dor-1222	O9 V(n)p	15.11	...	0.39	18.6	-4.7	WFPC2	"
30 Dor-1429A	O3-4 V	15.88	...	0.55	18.6	-4.4	WFPC2, also sublum	"
N81-1	O6-8:	14.38	...	0.07	19.1	-4.9	y , also wk wind	Heydari-Malayeri et al. 2002
N81-2	O6-8:	14.87	...	0.06	19.1	-4.4	y , also wk wind, sublum	"
N81-3	O6-8:	16.10	...	0.10	19.1	-3.3	y , also wk wind, sublum	"
N81-11	O6-8:	15.74	...	0.07	19.1	-3.6	y , also wk wind, sublum	"
<i>Subluminous (or $R > 3$?)</i>								
30 Dor-83	O9-9.5 V	15.44	-0.02	0.29	18.6	-4.0		Walborn & Blades 1997
30 Dor-324	O7-8 V	15.18	0.04	0.36	18.6	-4.5		"
30 Dor-466	O9 V	15.55	-0.11	0.20	18.6	-3.6		"
30 Dor-661	O3-6 V	15.03	0.14	0.46	18.6	-5.0		"
30 Dor-713	O3-6 V	14.61	0.03	0.35	18.6	-5.0		"
30 Dor-791	O3-5 V	15.84	0.31	0.63	18.6	-4.6		"
30 Dor-1035	O3-6 V	14.73	-0.05	0.27	18.6	-4.7		"
30 Dor-1170	O3-6 V	15.94	0.14	0.46	18.6	-4.0		"
<i>Normal V Comparisons</i>								
HD 46149	O8.5 V	7.56	0.17	0.48	10.5	-4.9	$R = 4$	Walborn & Fitzpatrick 1990
HD 46150	O5 V((f))	6.72 _v	0.13	0.45	10.5	-5.6	$R = 4$	Walborn et al. 2002b
HD 46202	O9 V	8.17	0.17	0.48	10.5	-4.2	$R = 4$	Martins et al. 2005
HD 46223	O4 V((f+))	7.25	0.22	0.54	10.5	-5.4	$R = 4$	"
15 Mon	O7 V((f))	4.65	-0.25	0.07	9.4	-5.0		Walborn & Fitzpatrick 1990
HD 93027	O9.5 V	8.72	-0.02	0.28	12.2	-4.3		"
HD 93028	O9 V	8.36	-0.06	0.25	12.2	-4.6		Martins et al. 2005
HD 93204	O5 V((f))	8.42	0.10	0.42	12.2	-5.0		"
HDE 303308	O4 V((f+))	8.17	0.13	0.45	12.2	-5.4		Walborn et al. 2002b
<i>Notes:</i>								
$(B - V)_0$: O2-O7, -0.32; O8-O9, -0.31; O9.5, -0.30								
$(b - y)_0 = -0.15$; $E(B - V) = 1.49E(b - y)$ (Heydari-Malayeri et al. 2001, 2002)								
$R = 3$ unless otherwise noted								

TABLE 1. *Continued*

complete to the author’s knowledge as of May 2006, although further candidates are being discovered as of this writing, e.g., in the SMC cluster NGC 346 by Evans et al. (2006), and in a new LMC fiber survey by I. Howarth (private communication). The sample is divided into five categories according to the distinct, principal discovery criteria, although many of them actually display more than one, as noted in the Comments. Three of these criteria are spectroscopic, one is environmental, and one is photometric. Discovery and/or data references are included in the Table. The five categories will now be discussed in turn.

2.1. *Vz spectra*

A luminosity classification for stars earlier than spectral type O9 was introduced by Walborn (1971, 1972, 1973a). It is based upon the selective emission effects (Walborn 2001) in He II $\lambda 4686$ and the N III triplet $\lambda\lambda 4634\text{--}4640\text{--}4642$, i.e., the Of phenomenon. These same lines display a *negative* effect in absorption with increasing luminosity in the MK O9–B0 classification, which was hypothesized to be caused by filling in of the absorptions by the same emission effects producing the Of phenomenon, thus providing the basis for a luminosity classification at the earlier types. A luminosity sequence at spectral type O6.5 in modern digital data is shown in Figure 1. As can be seen there, this He II line is a strong absorption feature in class V, which then weakens, neutralizes, and finally comes into emission above the continuum in the Ia supergiant. (Correlatively, the N III, already weakly in emission at class V, increases in strength with increasing luminosity.)

Walborn (1973) first noted that in the Trumpler 14 O-dwarf spectra, the $\lambda 4686$ absorption appeared stronger relative to the other He lines than in typical class V spectra. This very compact cluster in the Carina Nebula appears to be very young; it contains the O2 If* prototype, likely pre-WN object HD 93129A (Walborn et al. 2002b). Penny et al. (1993) found that this cluster is approximately 550,000 years old, while Repolust et al. (2004) derived an age of 150,000 years for HD 93128. Subsequently, even more extreme examples were found in the LMC giant H II regions 30 Dor and N11 (Parker et al. 1992; Walborn & Parker 1992; Parker 1993; Walborn & Blades 1997). Some of the N11 spectra are reproduced in Figure 2, and some new Galactic examples kindly provided for this presentation by V. Niemela and N. Morrell are shown in Figure 3.

A fairly obvious hypothesis is that the stronger $\lambda 4686$ absorption in these probably very young objects is an “inverse” Of effect, or more precisely, that typical class V spectra already have some emission filling in that line while these objects have less, and hence may be less luminous and less evolved, i.e., nearer to the ZAMS. To denote that hypothesis, the luminosity class notation Vz has been introduced. Some analytical support has been provided by the work of Venero, Cidale, & Ringuelet (2002), Martins et al. (2005), and Mokiem et al. (2006), but a homogeneous analysis of the full sample in high-resolution data with state-of-the-art photospheric/wind models is essential to investigate whether the Vz stars as a class have systematically higher gravities and lower luminosities than class V. In Table 1, the three blocks of Vz stars correspond to the Galaxy, LMC, and SMC.

A misunderstanding of the Vz definition in late-O spectra should be clarified here. At early O types, the He II $\lambda 4686$ absorption should be stronger than He II $\lambda 4541$. At type O7, He II $\lambda 4541$ is equal to He I $\lambda 4471$, so that $\lambda 4686$ is stronger than both in a Vz spectrum. At later O types, however, $\lambda 4541$ weakens more rapidly with advancing type than $\lambda 4686$ in normal class V spectra; thus, a late-O Vz spectrum must have $\lambda 4686$ *stronger than He I $\lambda 4471$* .

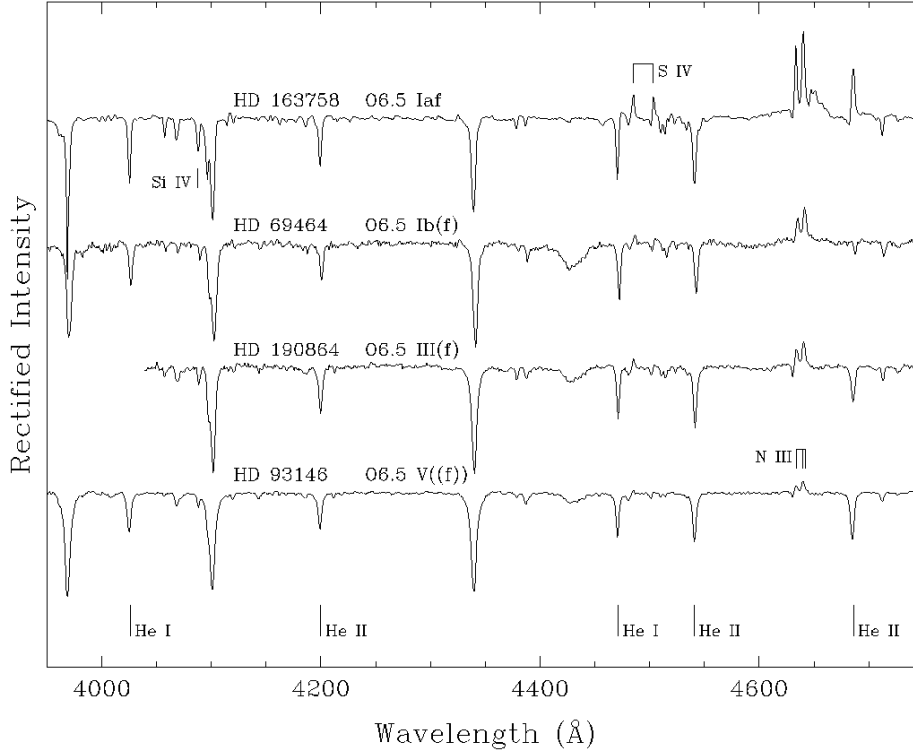


FIGURE 1. A luminosity sequence at spectral type O6.5. The rectified spectrograms are separated by 0.4 continuum units. The spectral lines identified below are He I $\lambda\lambda 4026, 4471$ and He II $\lambda\lambda 4200, 4541, 4686$. N III $\lambda\lambda 4634-40-42$ emission is marked above HD 93146, likewise Si IV $\lambda 4089$ and S IV $\lambda\lambda 4486-4504$ (Werner & Rauch 2001) in HD 163758. Note the comparable strengths of the $\lambda\lambda 4541, 4686$ absorptions in the class V spectrum, and the weakening, then transition to emission of the latter with increasing luminosity, while the N III emission increases smoothly. The Si IV absorption has a positive luminosity effect, which is more sensitive at later types. Courtesy of Ian Howarth.

2.2. Vb spectra

W. Morgan frequently remarked on a peculiarity of the Orion Nebula Cluster OB stars, namely broader Balmer lines than in normal class V spectra, with profiles that did not appear to be rotational; Morgan & Keenan (1973) reproduced photographic spectrograms of θ^1 Ori C and the O7 V standard 15 Mon to illustrate the effect. At some point, he introduced the notation Vb to denote such spectra, by analogy with Ib for less luminous supergiants and IIIb in Keenan's subdivision of late-type giants. (Abt 1979 cites a photographic atlas prepared with Morgan that appeared in 1978 as the source of the new notation, but it does not appear there.) Abt (1979) and Levato & Malaroda (1981, 1982) presented further examples among B and A dwarf spectra in very young clusters.

As for the Vz category, the question arises whether the Vb phenomenon might be caused by higher gravity and lower luminosity than in class V, since it is well known that the Balmer lines weaken with increasing luminosity in OB spectra due to the decreasing Stark effect. A careful analysis of the five OB components of θ^1 and θ^2 Ori has been presented by Simón-Díaz et al. (2006), including a thorough investigation of line-broadening mechanisms and comparison with standard objects (including 15 Mon) analyzed with the same techniques. Interestingly, they find that H and He lines in the

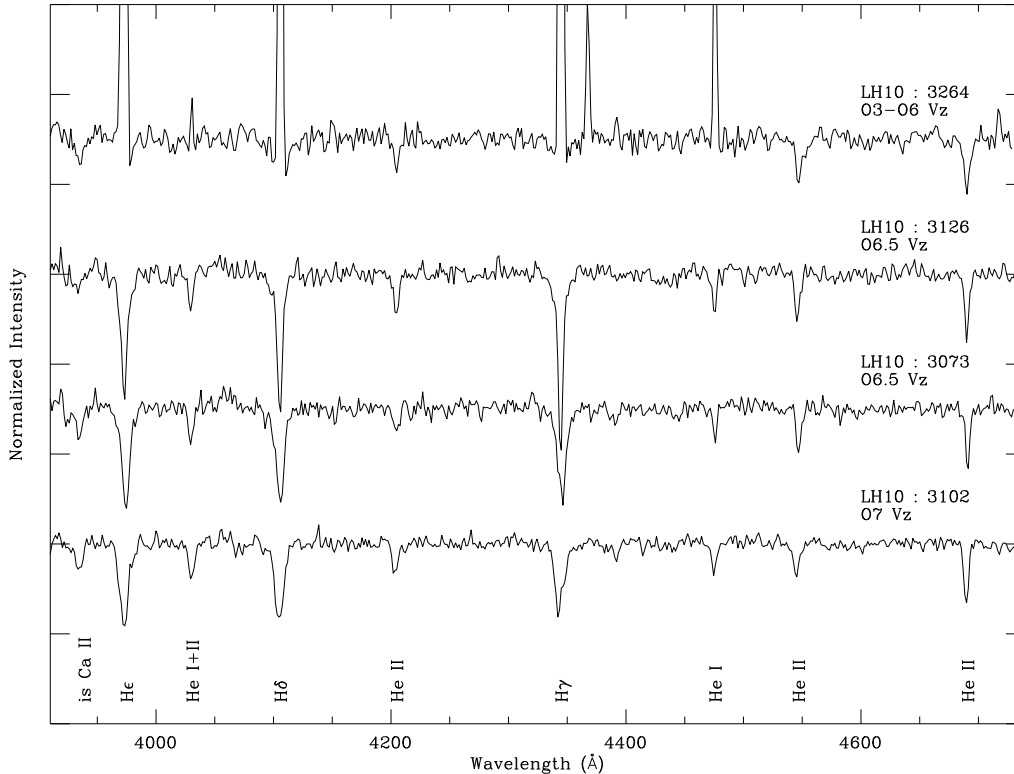


FIGURE 2. Vz spectra in Lucke-Hodge 10/Henize N11 in the LMC (Walborn & Parker 1992). The ordinate ticks are separated by 0.25 continuum units. See the Fig. 1 caption for identifications of the He lines. Note the increased strength of the He II $\lambda 4686$ absorption relative to the other He lines in these spectra, and also the great strength of the Balmer lines in LH10–3126. LH10–3264 is in the dense nebular knot N11A, which produces the very strong nebular emission lines. Courtesy of Joel Parker.

Orion stars tend to be broader than in the best fitting models, most systematically in the B0.5 V spectrum of θ^1 Ori D. However, they derive similar gravities to those of the comparison stars and find that the Orion stars are somewhat off the ZAMS, although uncertainties in the latter result remain because of the extinction law and, as they point out, the effect of initial rotational velocities on the location of the ZAMS. In Table 1, a value of $R = 4.25$ (average of 3.0 and 5.5) has been used to calculate the absolute magnitudes of the Trapezium stars, because the actual value in the Orion Nebula remains uncertain (Robberto et al. 2004); thus their subluminality is uncertain as well.

θ^1 Ori C is now known as the first O-type magnetic oblique rotator (Donati et al. 2002; Smith & Fullerton 2005; Gagné et al. 2005; Wade et al. 2006) and an extreme spectrum variable, including its abnormally weak UV wind profiles (Walborn & Nichols 1994; Stahl et al. 1996). Simón-Díaz et al. (2006) provide a detailed discussion of the effects of the variability on the quantitative analysis. Moreover, there is now evidence that the spectrum of 15 Mon may be variable as well; Simón-Díaz et al. also discuss the effects of its spectroscopic companion in that connection. Further quantitative analyses incorporating these complications are indicated to ascertain the nature of the Vb Balmer profiles and the physical origin of the peculiarity.

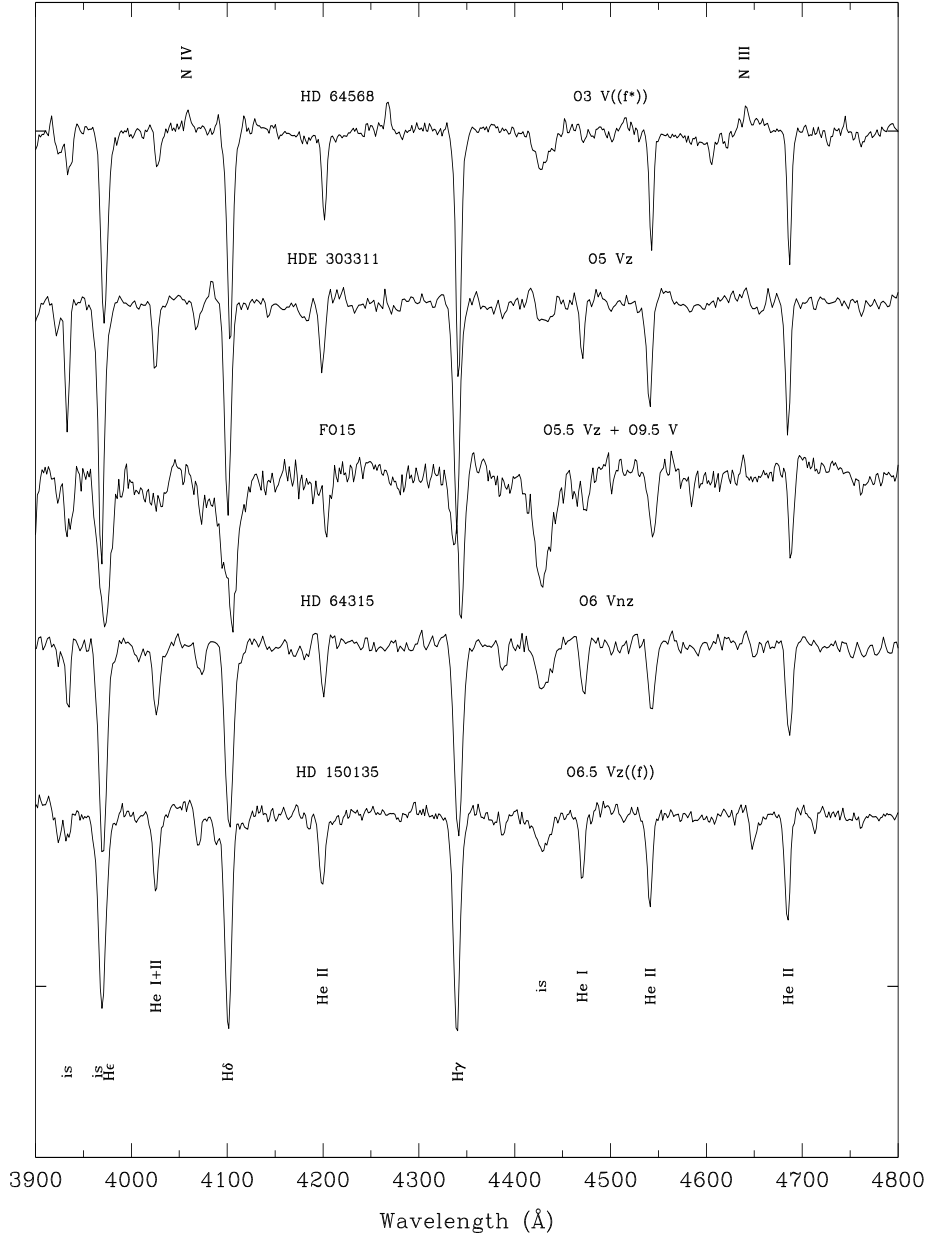


FIGURE 3. New Galactic Vz spectra, rectified and separated by 0.2 continuum units. See the Fig. 1 caption for identifications of the stellar lines; in addition, N IV $\lambda 4058$ emission is marked in HD 64568 here. Courtesy of Virpi Niemela and Nidia Morrell.

2.3. Weak winds

It is now well known that the ultraviolet stellar-wind profiles in O-type spectra display strong correlations with the optical spectral types, including an increase in strength with increasing luminosity (Walborn, Nichols-Bohlin, & Panek 1985). That study also detected four main-sequence stars with abnormally weak wind profiles for their spectral types, including θ^1 Ori C already discussed in the previous section. HD 5005A in the

young cluster NGC 281 is also located in a trapezium system, while HD 42088 ionizes the small, dusty H II region NGC 2175, which might appear knot-like (cf. next section) if it were at the distance of the Magellanic Clouds. Again, the inverse behavior of these weak wind profiles with respect to normal spectra suggests that these stars may be less luminous and less evolved than typical class V objects, but quantitative confirmation of this hypothesis is so far lacking. Martins et al. (2005) found a relatively weak wind for HD 42088, but a normal HRD location; however, the distance of this star is highly uncertain. (It should be noted that most of the stars in Table 1 have not yet been observed in the far UV.)

2.4. Nebular knots

Walborn & Blades (1987) reported the detection of O-type spectra in two dense nebular knots within the 30 Doradus Nebula in the LMC, suggesting that they might correspond to very young objects just emerging from their natal cocoons. Subsequent work, both from the ground and with *HST*, has amply confirmed that suggestion and revealed additional examples in 30 Dor (Walborn & Blades 1997, Walborn et al. 1999, 2002a); several have been resolved into multiple (trapezium) stellar systems by *HST*. The very strong nebular emission lines in these objects obliterate the stellar He I absorption and thus preclude accurate classification, as only the He II can be seen, leading to the O3-6 V type (there is no uncertainty in the luminosity class, which depends on only He II $\lambda 4686$); in fact, several examples re-observed spectroscopically with *HST*, its very high spatial resolution suppressing the nebular background, turn out to have even later O types than that range previously assigned from the ground (Table 1). The reddening and absolute magnitudes of these stars have kindly been derived by L. Úbeda from the WFPC2 photometry using the CHORIZOS code (Maíz-Apellániz 2004); a normal reddening law had to be adopted because of the limited wavelength coverage.

LH10–3264 (Parker et al. 1992, Walborn & Parker 1992; Fig. 3 here), which is also Vz, is another interesting case in the LMC compact H II region N11A; it has also been resolved into a multiple system with *HST* by Heydari-Malayeri et al. (2001), and the entry in Table 1 (N11A-7) corresponds to the brightest component. N81 is a similar object in the SMC, investigated with *HST* by Heydari-Malayeri et al. (2002); the weakness of the stellar-wind profiles in these stars may be caused by a combination of extreme youth and the SMC metal deficiency.

2.5. Subluminosity

In the spectroscopic study of the 30 Doradus stellar populations by Walborn & Blades (1997), the derived absolute magnitudes for a number of the O V stars fall below the calibration of that luminosity class (cf. their Fig. 3). Those that are not also classified as Vz are listed separately in Table 1. It is reasonable to hypothesize that they may be nearer to or on the ZAMS. However, a basic uncertainty, which also applies to some subluminous cases discussed in the previous sections, must be recognized: because of the lack of further information, the absolute magnitudes have to be derived with a normal value of $R = 3$. For a fixed distance modulus and variable extinction, a larger value of R would yield brighter absolute magnitudes. To resolve this issue, photometric observations covering a wider wavelength range (ideally, UV through IR) must be obtained to support the derivation of reddening laws toward each individual star. Indeed, there is evidence that the reddening law may vary among different lines of sight within a complex H II region environment, because of spatially diverse mixtures of dust grain properties. In any event, large values of R are associated with large dust grains and very young objects, so

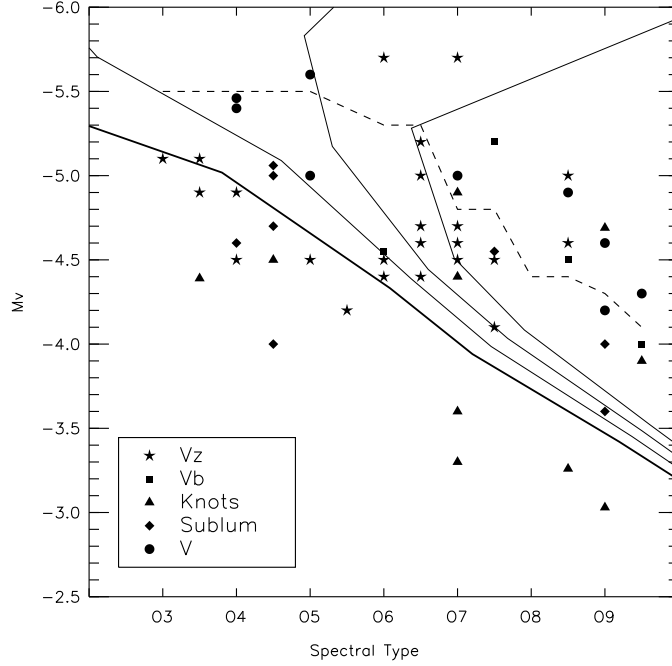


FIGURE 4. Derived absolute visual magnitudes for candidate ZAMS and normal O stars plotted against their spectral types. The bold solid line is the ZAMS from Schaller et al. (1992), while the lighter solid lines are the corresponding isochrones for 1, 2, 3 Myr. The dashed line is the luminosity class V calibration from Walborn (1973a). The normal stars fall near the latter, while most of the ZAMS candidates lie below it. Courtesy of Leonardo Úbeda.

these stars may be near the ZAMS in either case, but again, further observations and quantitative analyses are required to definitively establish their physical status.

3. Discussion

All of the absolute magnitudes from Table 1 are plotted against the spectral types in Figure 4, where they are also compared with the Schaller et al. (1992) ZAMS and isochrones, as well as the luminosity class V calibration (Walborn 1973). The different categories of ZAMS candidates are distinguished with different symbols. Subject to the uncertainties already discussed, the plot provides preliminary support for the present hypothesis: most of them fall below the class V calibration and near the ZAMS. Note that HD 93128 lies adjacent to the ZAMS, in agreement with the detailed analysis of Repolust et al. (2004). The normal class V stars cluster about the calibration, as well they should since they contributed to its derivation. Interestingly, the figure shows that a typical O3 V star is 1 Myr old, O5 V 2 Myr, O6–7 V 3 Myr, and O8–9 V perhaps 4–5 Myr. Less luminous stars at a given type must be younger. It is also clear that unresolved multiple systems move points upward in the diagram (recall that 0[′].1 corresponds to 5000 AU at the LMC), while underestimated values of R move them downward.

The present sample of candidate ZAMS stars is optimum for followup with high-resolution spectroscopy and state-of-the-art atmospheric/wind analysis. Beyond the basic question of their ZAMS status or otherwise, it may be hoped that such study will elucidate any sequential relationships among the different categories, thereby advancing our detailed understanding of early massive stellar evolution.

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